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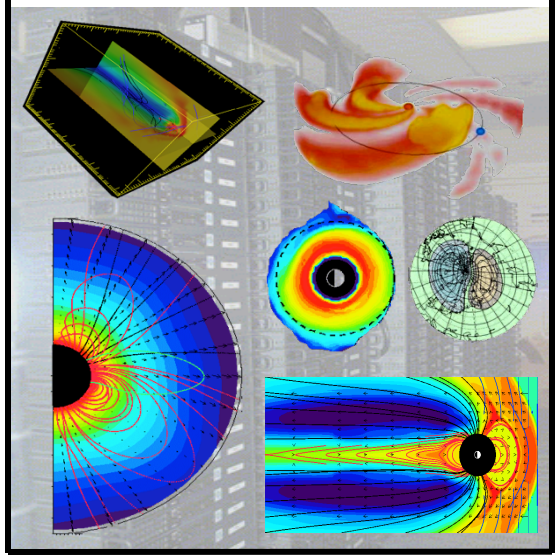

Modeling and validation of neutral density in high altitude regions

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Abstract

There has been a growing concern about orbital collisions that will occur more frequently. One of the main sources of errors in orbit determination is uncertainty in the atmospheric density. As a result, accurate specification and prediction of neutral density is crucial to avoid potential disasters both in LEO and higher altitude regions. In this paper, we focus on modeling of neutral density in altitude regions higher than the upper limit of most physics-based atmosphere models, which are limited to a top pressure level of about 10^{-7} Pa where the fluid approximation becomes no longer valid. To model neutral density at the altitude higher than 600 km, we introduce a simplified algorithm to extrapolate neutral density to greater altitudes. Using the extrapolation formula and thermospheric outputs obtained from a physic-based model, CTIPe (Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics), we calculate neutral density along the satellite track such as CALSPHERE 02826 (near 800 km orbit) during quiet periods in 2003 and 2004 and geomagnetic storms as well. We will present preliminary results of the study and compare CTIPe orbital averaged neutral density values with HASDM (High Accuracy Satellite Drag Model) data, the JB2008 and NRLMSISE-00 model values.

Neutral Density Calculation at High Altitude (> 600 km)

- Limited altitude range of physics based models
- Use a simple algorithm to extrapolate neutral density to greater altitudes, above the top boundary of the neutral atmosphere in the models:
  - algorithm assumes diffusive equilibrium for the three major species O, O_2, and N_2.
  - number density at a given height h above the height of the top pressure level ht(15) (~ 10^{-7} Pa),

    $n(O,h) = n(O,15) \times \exp((ht(15)-h) / H(O))$ m^{-3},

    $n(O_2,h) = n(O_2,15) \times \exp((ht(15)-h) / H(O_2))$ m^{-3},

    $n(N_2,h) = n(N_2,15) \times \exp((ht(15)-h) / H(N_2))$ m^{-3},

    where H(X) : scale height of the species, (= $RT(15)/M_X g$),
    - use T at the top level pressure 15 and assume constant above
    - $g = g_0(r_e/(r_e+h))^2$

- mass density at any height h

  $= (n(O,h) \times 16. + n(O_2,h) \times 32. + n(N_2,h) \times 28.) \times$ amu kg/m^3

Setup for Validation

- Time Intervals
  - quiet periods & moderate storm
    - E.2003.200 (200 – 220) : Dst_min = -60 nT, F107_ave = 130
    - E.2004.218 (218 – 228) : Dst_min = -55 nT, F107_ave = 115

  - Strong storms
    - E.2003.323 (323 – 330) : Dst_min = -420 nT, F107_ave = 133
    - E.2003.301 (301 – 308) : Dst_min = -380 nT, F107_ave = 134
    - E.2004.311 (311 – 319) : Dst_min = -370 nT, F107_ave = 102
    - E.2004.204 (204 – 212) : Dst_min = -200 nT, F107_ave = 112
    - E.2003.228 (228 – 235) : Dst_min = -150 nT, F107_ave =124

- Models are validated against the neutral density along the CALSPHERE 02826 satellite (near 800 km orbit) obtained by semi-empirical model, HASDM.

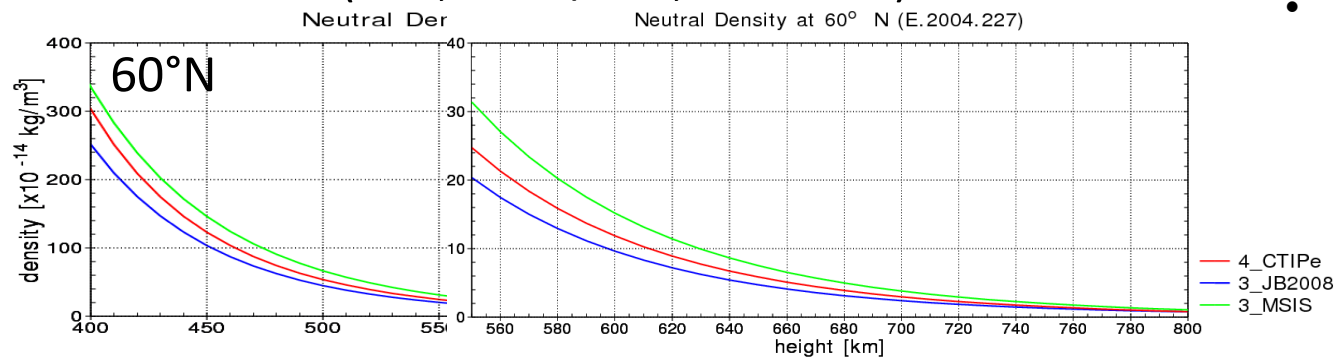
Model Submissions

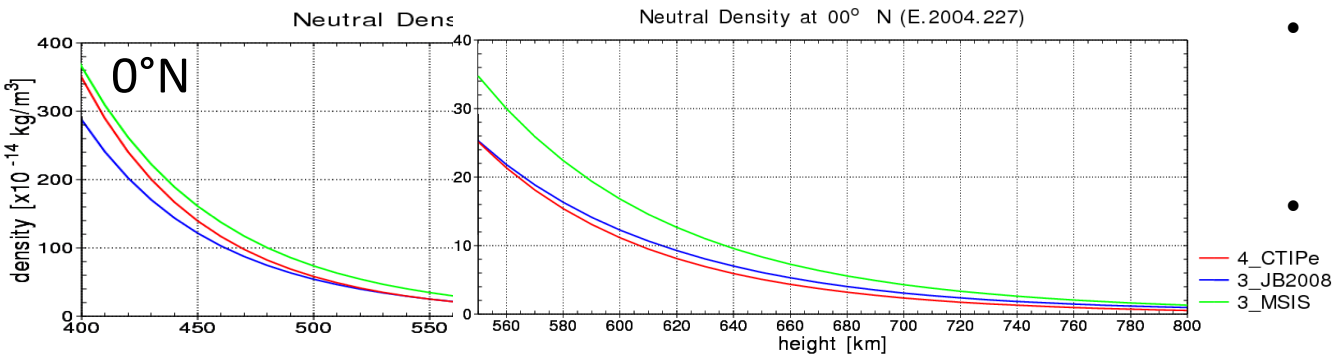
	Model Setting ID	
1	HASDM	• Semi-empirical model based on Jacchia 70 and DCA (Dynamic Calibration Atmosphere) program using AF Space Surveillance Network observations every orbit from multiple radars • Produces density corrections every 3 hours using multiple calibration satellites (~80-90) consisting of spheres, R/B, debris at altitudes from 200 to 800 km
2	3_MSIS	• NRLMSISE-00, empirical model • Inputs: F10.7 and Ap index
3	3_JB2008*	• JB2008 empirical thermospheric density model by Bruce Bowman, Kent Tobiska, et al. • Dst index is primarily used to indicate the strength of the storm-time ring current
8	4_CTIPE*	• CTIPe, physics-based coupled IT model • driven by Weimer electric potential model

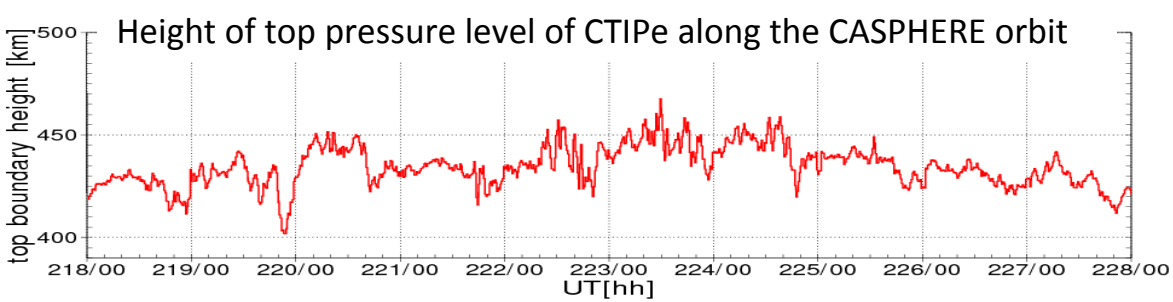
* Runs performed at the CCMC

Modeled Neutral Density Height Profile
during quiet time & moderate storm

E.2004.218 (0°E, 2004/227, 12:45 UT)



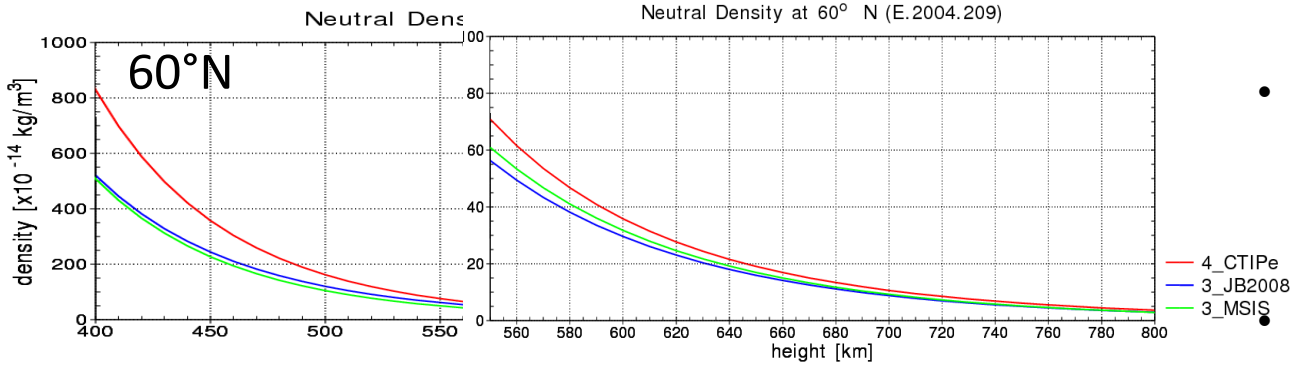


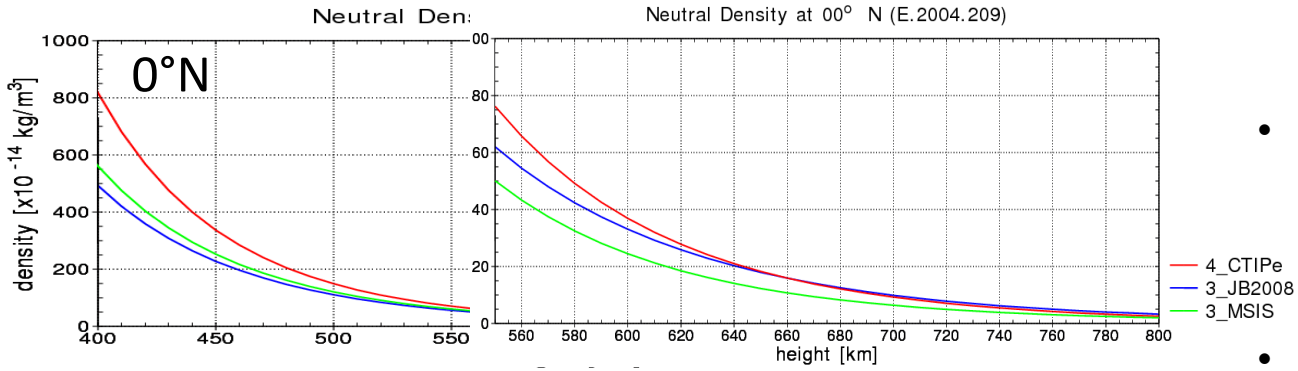


- CTIPe neutral density profiles are obtained by using the simple algorithm to extrapolate the values to greater altitudes, above the top boundary of the the model.
- CTIPe results are compared with are JB2008 and MSIS results
- CTIPe neutral density values above the above the top boundary are similar to those of the other two empirical models.
- MSIS density values are larger than other models' density values.

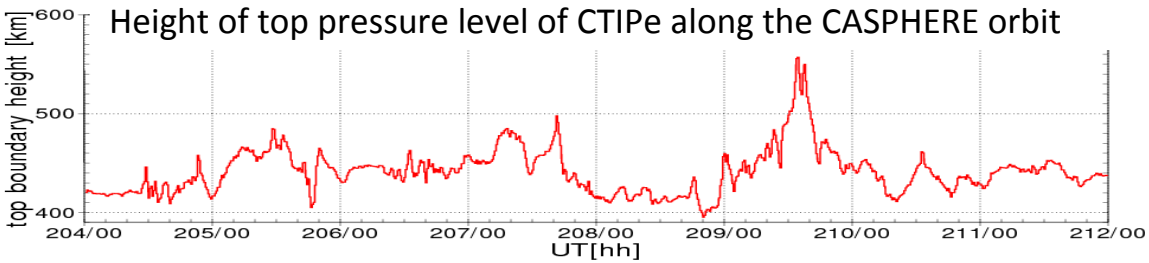
Modeled Neutral Density Height Profile during strong storm

E.2004.204 (0°E, 2004/209, 12:45 UT)





Height of top pressure level of CTIPe along the CASPHERE orbit



- CTIPe produces larger density than other models' density during E.2004.204 strong storm event.
- Height of the top pressure level reaches up to 570 km during the event.
- Above 650 km, CTIPe and JB2008 show similar density profiles in both low and high latitudes.
- The simple formula, which is used to extrapolate the values to greater altitudes, produces neutral density comparable to the results of JB2008 and MISIS

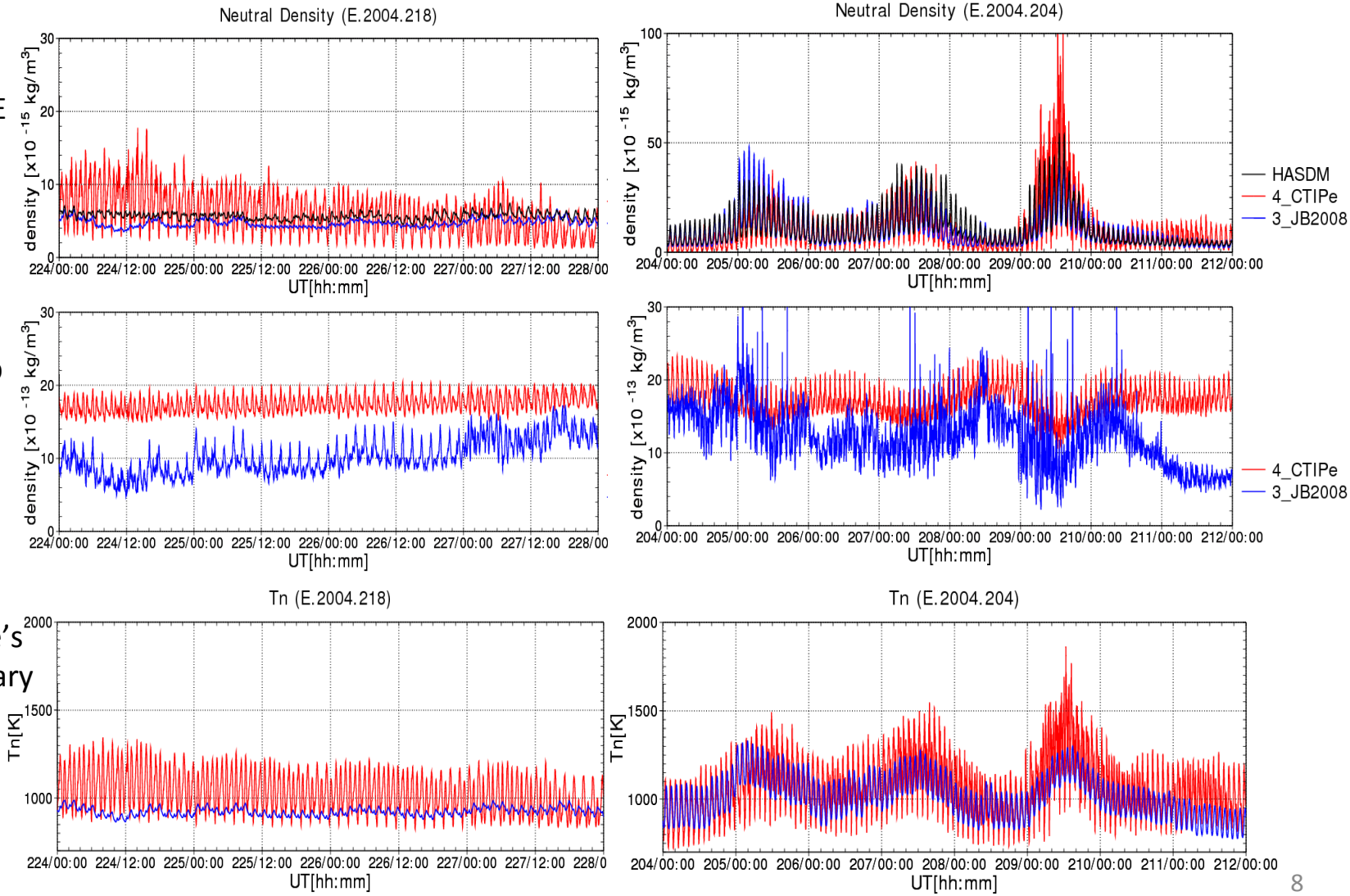
Modeled Neutral Density & Tn along CALSPHERE Orbit

E.2004.218 E.2004.204

Density at CALSPHERE trajectory

Density at CTIPe's top boundary

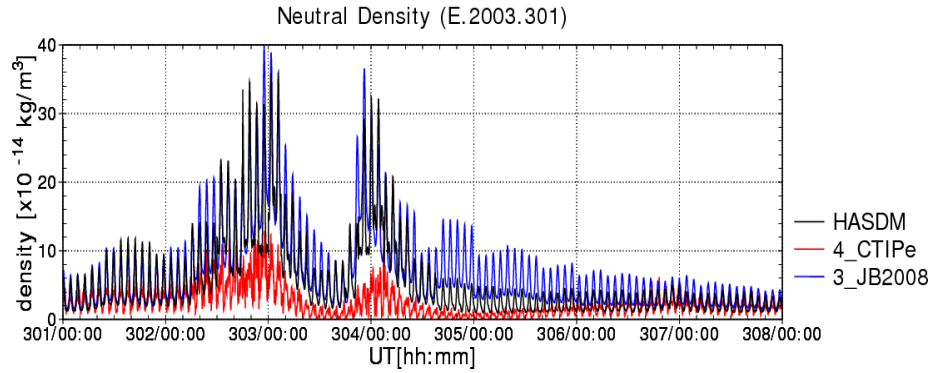
Tn at CTIPe's top boundary



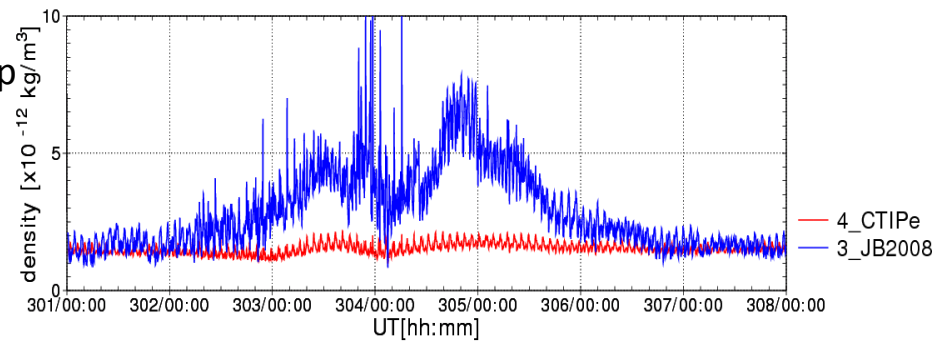
Modeled Neutral Density & Tn along CALSPHERE Orbit

E.2003.301

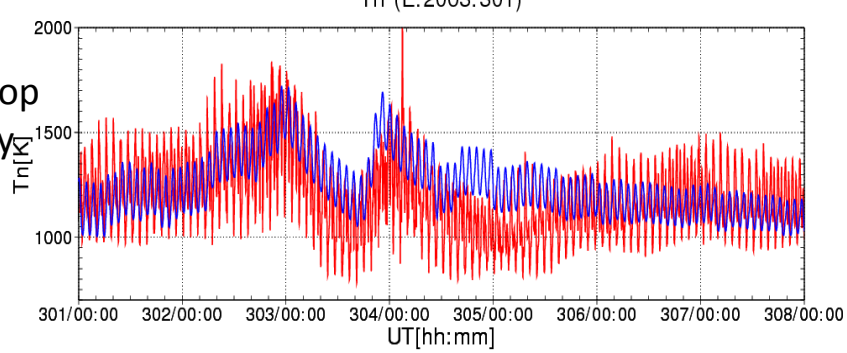
Density at CASPHERE trajectory



Density at CTIPe's top boundary

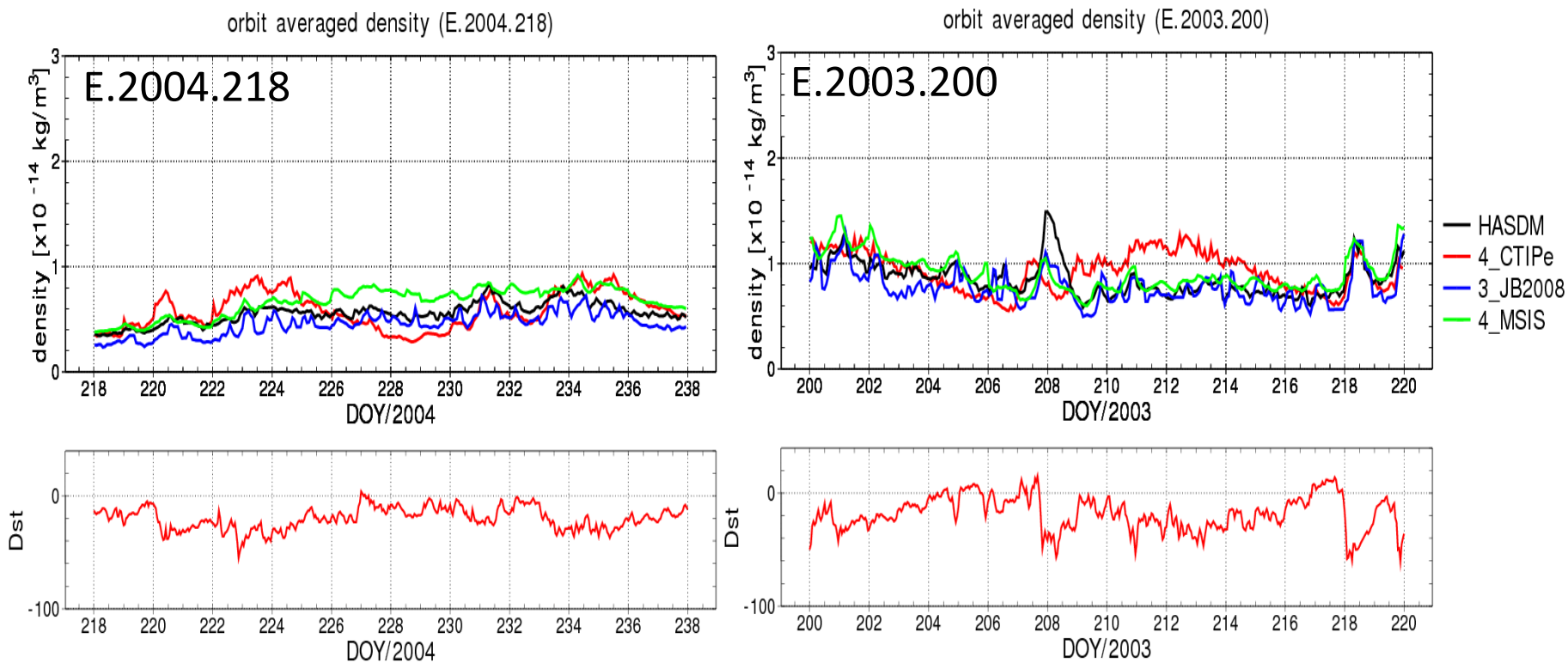


Tn at CTIPe's top boundary



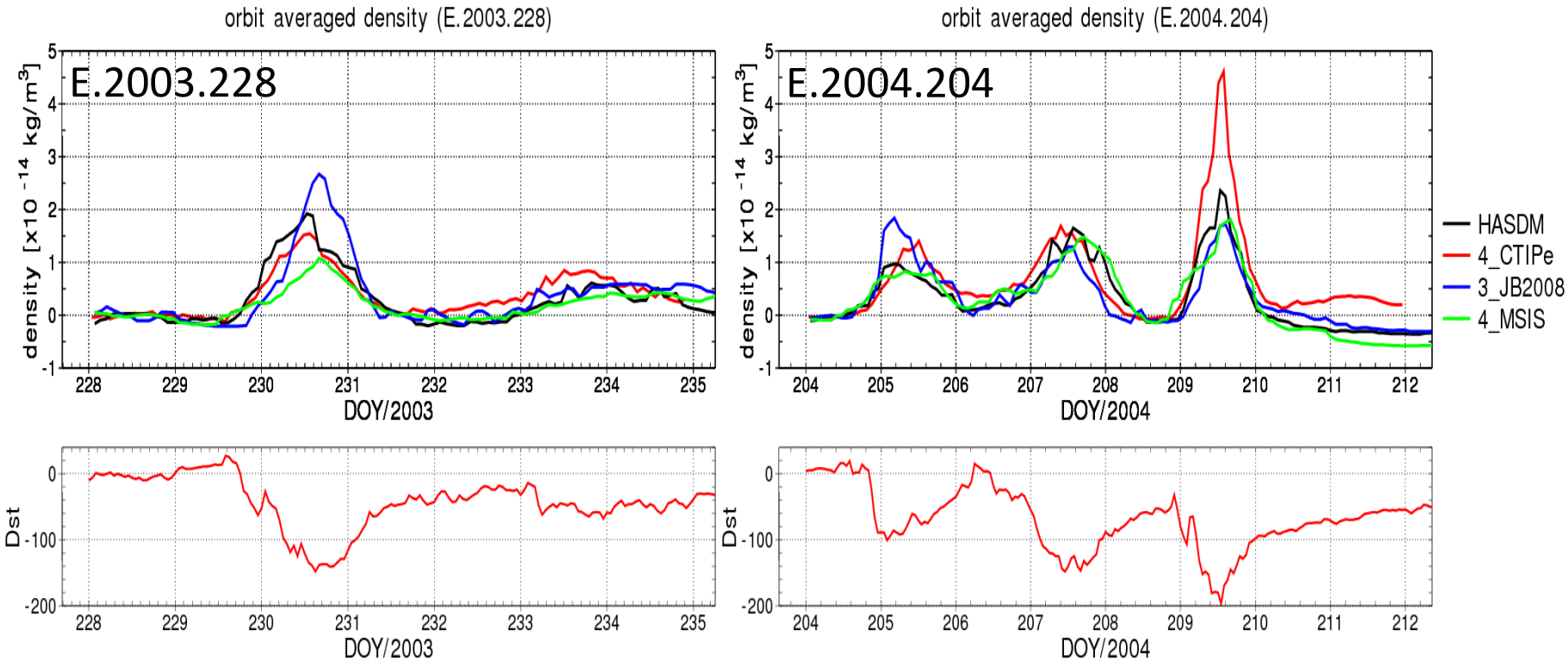
- JB2008 and HASDM show smaller latitudinal and local time variations of neutral density and temperature during quiet time & moderate storm (E.2004.218) than CTIPe.
- During E.2004.204 event, JB2008 and CTIPe shows similar density and temperature at CALSPHERE orbit, while JB2008 produces larger density at CTIPe's top boundary height than CTIPe.
- For E.2003.301 event, CTIPe produces smaller density (and variation) than HASDM and JB2008

Orbit Averaged Neutral Density (OAND) at CALSPHERE Orbits during quiet time & moderate storms



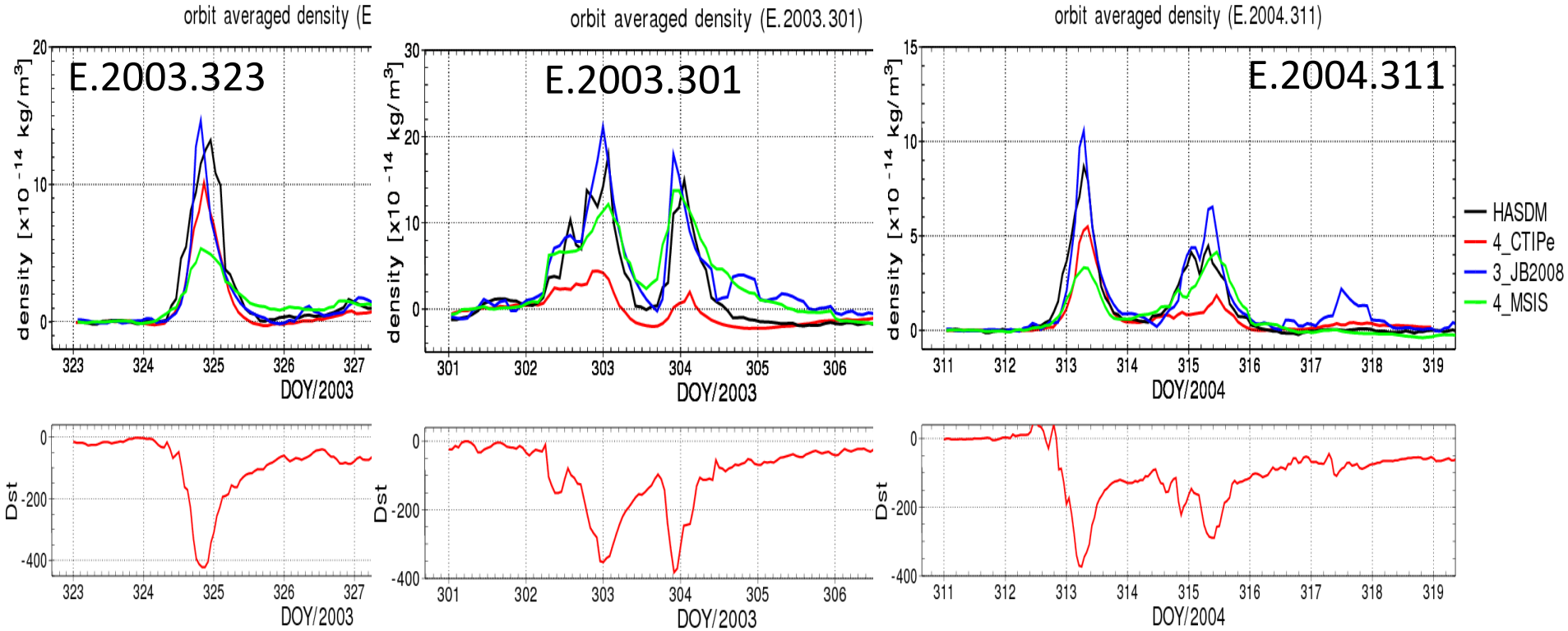
- CTIPe tends to produce larger neutral density values during moderate storms and smaller values during quiet times than HASDM.
- During moderate storms in 2004 (E.2004.218), MSIS has larger neutral density and JB2008 has smaller density than HASDM.

Strong Storms (-200 nT < Dst_min < -100 nT)



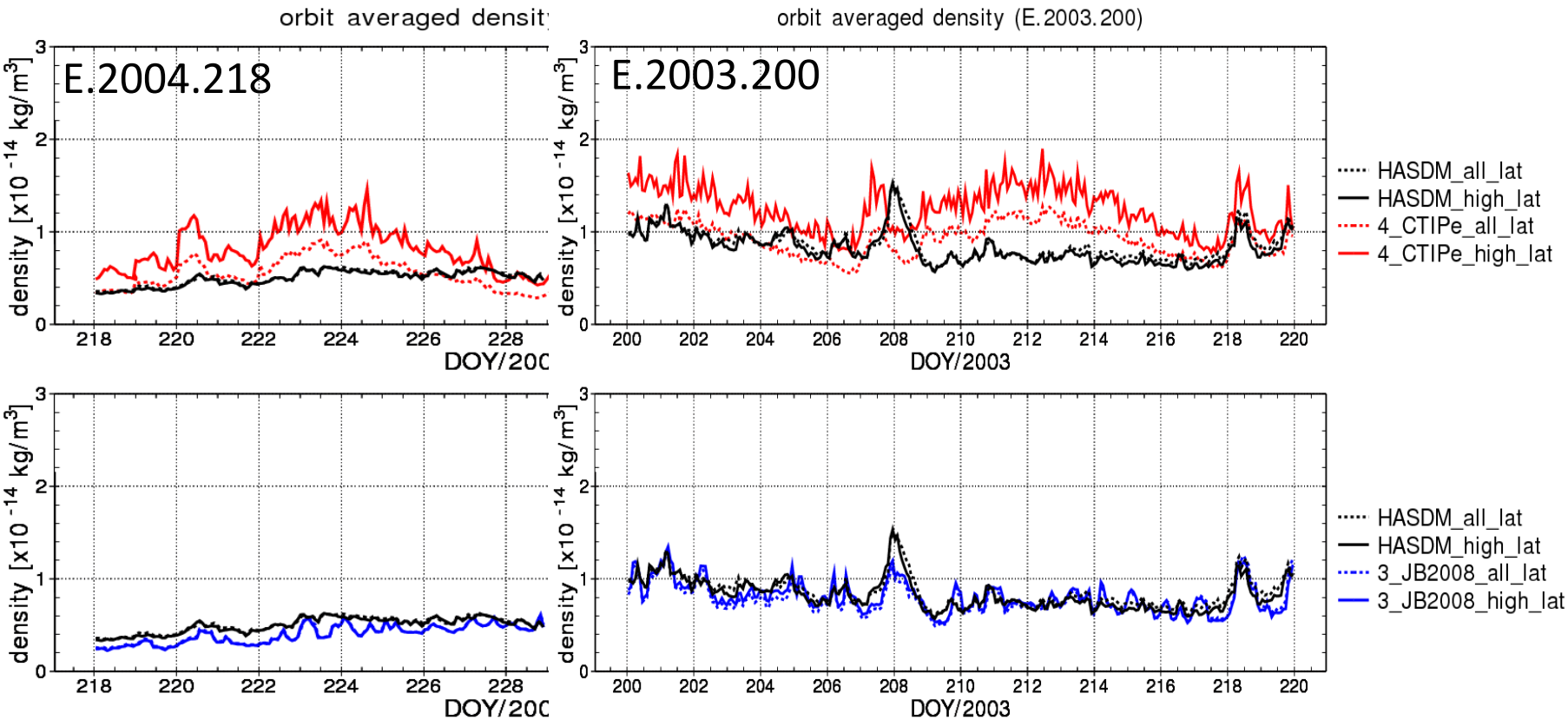
- Modeled values are shifted to zero by subtracting quiet time mean neutral density (a day before the storm) of each model simulations.
- CTIPe density values well agrees with HASDM although CTIPe density is about twice HASDM density for third storm of E.2004.204 event (Dst = -200 nT)

Strong Storms (Dst_min ≈ -400 nT)



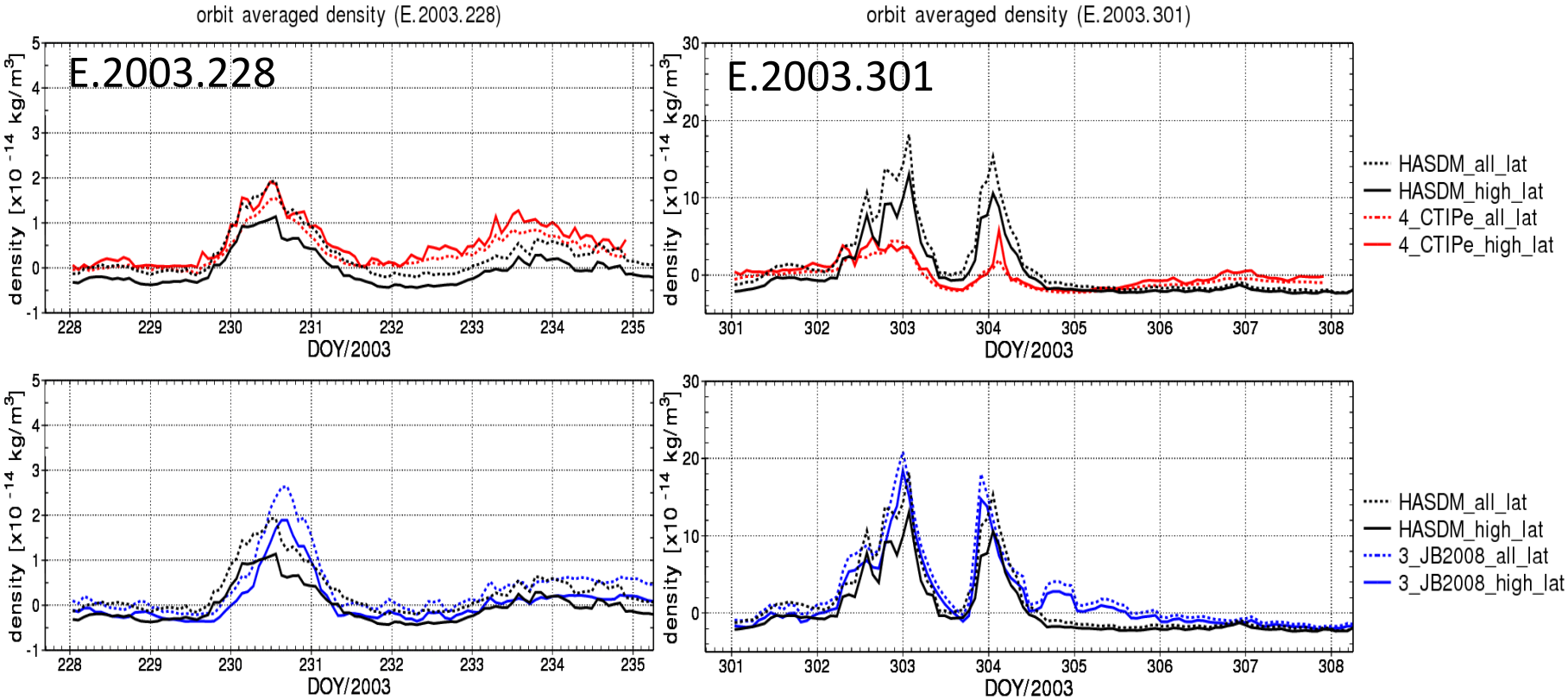
- Compared to HASDM, JB2008 produces larger peak density, while CTIPe and MSIS tend to produce lower peak density values.
- For E.2003.301, CTIPe produces much lower orbit averaged neutral density values than the others.

High Latitude Orbit Averaged Density (|lat| > 60°) during quiet time & moderate storms



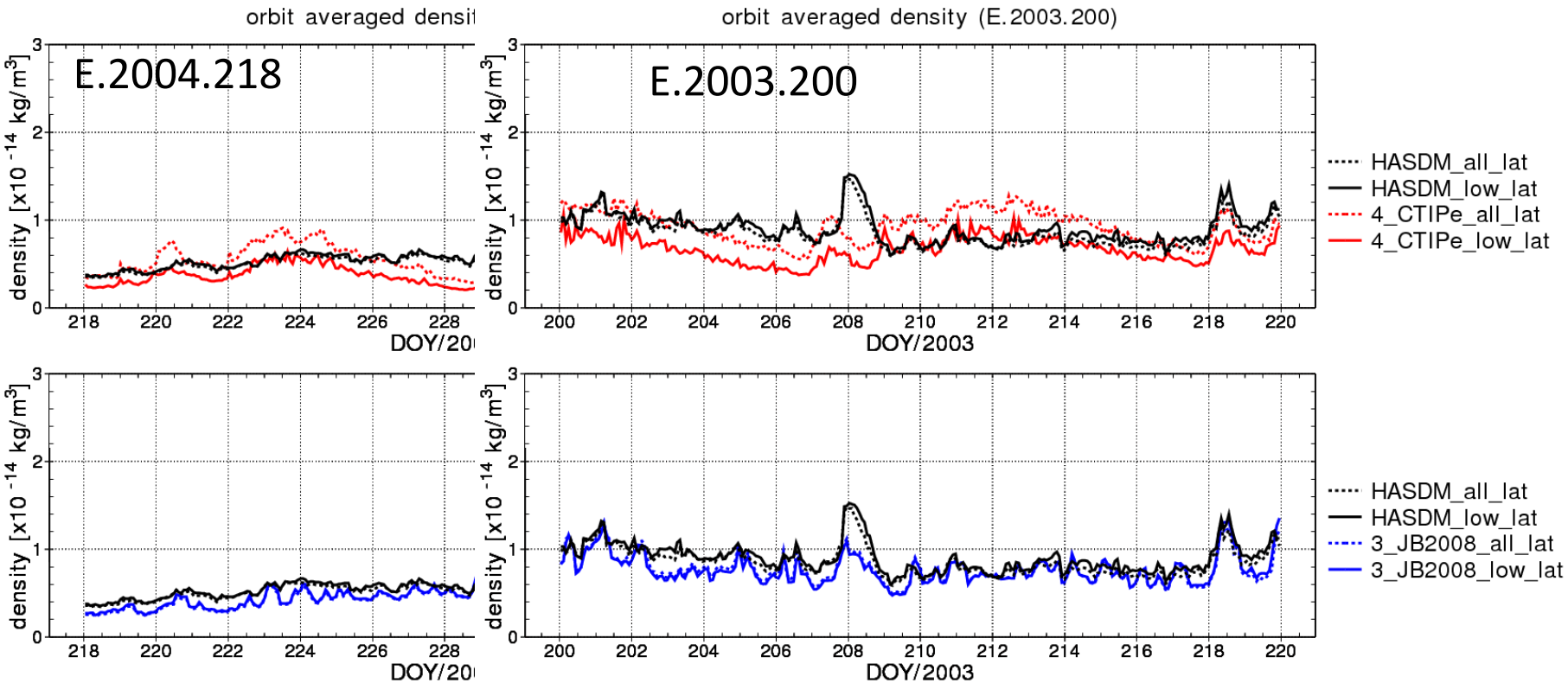
- CTIPe shows noticeable difference in orbit averaged neutral density between over all latitude regions and over only latitude regions higher than 60 degrees, while JB2008 and HASDM hardly show the difference between them.

Strong Storms (-200 nT < Dst_min < -150 nT)



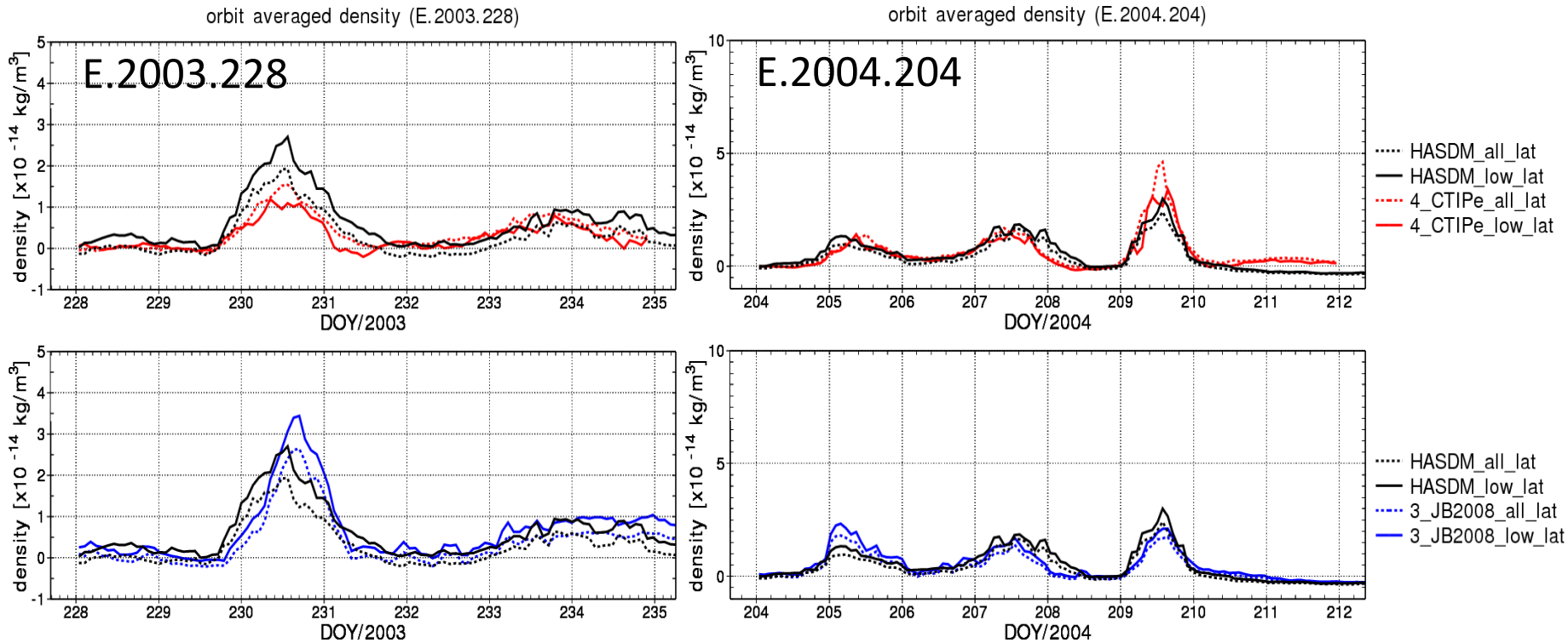
- CTIPe produces larger orbit averaged density when the values are averaged over only latitude regions higher than 60 degrees.
- JB2008 and HASDM tend to produce larger orbit averaged density when the values are averaged over all latitude regions.

Low Latitude Orbit Averaged Density (|lat| < 20°) during quiet time & moderate storms



- CTIPe produces smaller orbit averaged density when the values are averaged over only latitude regions lower than 20 degrees.
- JB2008 and HASDM hardly show the difference between them.

Strong Storms (-200 nT < Dst_min < -150 nT)



- For E.2003.228 event, HASDM and JB2008 produces larger orbit averaged density when the values are averaged over only latitude regions lower than 20 degrees, while the opposite holds true for CTIPe. Therefore, difference between CTIPe and HASDM is larger in orbit averaged density (OAND) over low latitude than OAND over all latitude regions.

RMS Error (x 10^{-15} kg/cm^3)

RMS error against HASDM = $\sqrt{\frac{\sum (x_{HASDM} - x_{mod})^2}{N}}$

Average over all latitudes	Without shift			With shift		
	CTIPE	JB08	MSIS	CTIPE	JB08	MSIS
Quiet times & moderate storms						
E.2003.200	2.44	1.34	1.42	2.54	1.14	10.4
E.2004.218	1.47	1.14	1.29	1.46	0.52	4.65
average	**1.96**	**1.24**	**1.35**	**2.00**	**0.83**	**7.55**
Strong storms						
E.2003.323	11.6	11.8	18.0	12.0	11.8	23.6
E.2003.301	46.6	24.7	30.5	40.3	22.7	65.3
E.2004.311	13.8	7.25	10.1	10.7	7.65	13.9
E.2004.204	4.29	3.32	3.77	5.20	3.12	10.6
E.2003.228	2.23	3.40	3.16	2.34	3.48	9.30
average	**15.7**	**10.1**	**13.1**	**14.1**	**9.75**	**24.6**

- JB2008 performs better than CTIPe and MSIS for most cases.
- Before shifting data to zero, CTIPe show similar scores to MSIS, while after shifting CTIPe scores are better than MSIS scores.
- MSIS has larger RMS error after shifting data, while CTIPe and JB2008 do not show big difference between the scores without shifting and with shifting.

RMS Error (x 10^{-15} kg/cm^3) : High Latitude OAND

Average over high latitudes	Without shift			With shift		
	CTIPE	JB08	MSIS	CTIPE	JB08	MSIS
Quiet times & moderate storms						
E.2003.200	4.98	1.14	2.72	3.11	1.12	12.2
E.2004.218	3.87	1.24	1.80	2.36	0.53	5.09
average	**4.43**	**1.13**	**2.23**	**2.74**	**0.82**	**8.63**
Strong storms						
E.2003.323	10.1	11.0	13.2	10.9	11.2	21.2
E.2003.301	30.1	24.5	39.3	33.3	20.5	62.7
E.2004.311	9.19	6.92	10.2	7.93	7.02	14.9
E.2004.204	7.31	2.99	7.35	8.01	2.74	12.7
E.2003.228	5.29	2.97	2.68	3.15	2.96	9.28
average	**12.4**	**9.69**	**14.5**	**12.7**	**8.87**	**24.2**

- The models show the worst performance in predicting the orbit averaged density for E. 2003.301 (the Halloween storm).
- For quiet times and moderate storms, CTIPe and MSIS have larger RMS error for high latitude averaged density than the error for all latitude averaged values.

- CTIPe and MSIS performs better than others for E.2003.323 and E.2003.228 and storm event, respectively.

RMS Error (x 10^{-15} kg/cm^3) : Low Latitude OAND

Average over low latitudes	Without shift			With shift		
	CTIPE	JB08	MSIS	CTIPE	JB08	MSIS
Quiet times & moderate storms						
E.2003.200	3.22	1.84	2.22	2.46	1.41	8.51
E.2004.218	1.84	1.17	0.75	1.07	0.51	3.83
average	**2.53**	**1.51**	**1.50**	**1.77**	**0.96**	**6.17**
Strong storms						
E.2003.323	18.8	13.0	22.7	18.1	13.2	26.5
E.2003.301	67.2	27.3	33.7	53.7	26.7	69.3
E.2004.311	18.6	8.04	13.6	13.8	9.03	16.2
E.2004.204	5.62	3.94	3.97	4.12	3.77	9.48
E.2003.228	6.05	3.80	5.45	4.40	3.81	10.1
average	**23.2**	**11.2**	**15.9**	**18.8**	**11.3**	**26.3**

- For most cases, the models have larger RMS error for low latitude averaged density than the error for all latitude averaged values.
- RMS errors of JB2008 are smaller than those of CTIPe and MSIS for most cases.
- MSIS performs better than others for E.2004.218 event before shifting data.
- CTIPe has smaller RMS errors after shifting data than before shifting.

- Data shifting hardly produces difference in RMS errors of JB2008 between the scores without shifting and with shifting.

Summary of IT model performance

for orbit averaged neutral density prediction in high altitude regions

- A simple algorithm is used to extrapolate neutral density to greater altitudes, above the top boundary of the neutral atmosphere in the physics-based model, CTIPe.
- CTIPe, JB2008 and NRLMSISE-00 are validated against orbital averaged neutral density values along the CALSPHERE orbits obtained by HASDM (High Accuracy Satellite Drag Model) data.
- The simple formula, which is used to extrapolate the values to greater altitudes, produces neutral density comparable to the results of the empirical models, JB2008 and MISIS.
- The modeled values are shifted to zero by subtracting quiet time mean neutral density (a day before the storm) of each model simulations.
- The models' performance depends on the data shifting.
- The models show the worst performance in predicting the orbit averaged density for E.2003.301 event (the Halloween storm).
- Physics based and empirical models' performances are comparable.